ULTRASONIC STUDY OF QUASI-ISOTROPIC COMPOSITES

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INTRODUCTION

Advanced composites used for aerospace applications usually have multilayered structure with differently oriented plies. Most ultrasonic inspections of such composites are performed using normally incident ultrasonic waves. The use of oblique incident waves is complicated by strong ply scattering and difficulties in wave propagation analysis. In this paper we investigate both theoretically and experimentally ultrasonic wave propagation in multi-ply composites depending on ply orientation and angle of incidence. We compare computational efficiency and rederive algorithms for transfer and global matrix methods. Many authors have considered transfer matrix algorithm for isotropic and anisotropic cases [1-8]; however, the computational instability of the transfer matrix method when the layer thickness is comparable to and greater than the wavelength makes it impractical. Dunkin [9] and Levesque & Piche [10] have developed a stable transfer matrix method for the isotropic case. A stable method for the anisotropic case has been developed by Hosten and Castaings [11][12]. In contrast to the transfer matrix approach, the global matrix method assembles solutions for all layers in a single matrix which is large; however the method is computationally stable.

We apply both the transfer and global matrix methods to calculations of ultrasonic wave propagation in multi-ply composites. The transfer matrix analysis we base on the work of Hosten and Castaings[11][12]. We have rederived the δ matrix elements and simplified and reduced the number of matrix elements by using symmetries of the δ matrix. The computation time for both transfer matrix and global matrix methods are compared and the efficiency of each method is discussed. Experimental and computational examples are given for a 16-layer quasi-isotropic graphite epoxy composite for transmission and reflection arrangements. It is shown that the ultrasonic response does not exhibit isotropic behavior as observed, for example, in mechanical tests on quasi-isotropic composites. The amplitudes of the obliquely transmitted/reflected ultrasonic signals depend on the sample orientation relative to the incident plane as well as on ply orientation and ply sequence.

THEORY

We consider a composite plate immersed in fluid consisting of an arbitrary number n of orthotropic layers rigidly bonded at their interface and stacked normal to the z-axis of a global orthogonal Cartesian system (x, z) (Fig. 1). The thickness and the fiber direction of each lamina

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are h_i and ϕ_i, respectively, where i=1,2,......n. The thickness of the composite plate is $h = h_1 + h_2 + \cdots + h_n$.

Transfer Matrix Method

The global transfer matrix can be obtained from continuous boundary conditions of displacement (or particle velocity) and stress [5].

$$S_0^- = BS_n^+ ,\qquad B = \prod_{i=1}^{n} B_i \tag{1}$$

where S is the displacement (or particle velocity) and stress vector, and B_i is the 4×4 (for in plane of symmetry) or 6×6 (for out of plane of symmetry) displacement (or particle velocity) and stress matrix. Rokhlin shows that in the plane of symmetry B_i is inversely symmetrical and only 10 elements are independent. Also, the form of Rokhlin's transfer matrix can improve the stability in the numerical calculation of both reflected and transmitted waves [10].

The reflection and transmission coefficients for a fluid-loaded multilayered plate can be derived from Eq. (1); for an in-plane-of-symmetry anisotropic medium (2D case) we have

$$R_1 = a\left[aB_{6,1}^{\Delta 2} + bB_{6,2}^{\Delta 2}\right], \qquad R_2 = b\left[aB_{5,1}^{\Delta 2} + bB_{5,2}^{\Delta 2}\right]$$

$$R = (R_1 - R_2)/(R_1 + R_2), \qquad T = -2abb_{41}/(R_1 + R_2)\,. \tag{2}$$

where $B^{\Delta 2}$ is a 2nd (6×6) order delta matrix defined by Dunkin [9] and Levesque and Piche [10].

For an out-of-plane-of-symmetry anisotropic medium (3D case) we have

$$R_1 = a\left[aB_{20,1}^{\Delta 3} + bB_{20,2}^{\Delta 3}\right], \qquad R_2 = b\left[aB_{19,1}^{\Delta 3} + bB_{19,2}^{\Delta 3}\right],$$

$$R = (R_1 - R_2)/(R_1 + R_2), \qquad T = 2abB_{15,1}^{\Delta 2}/(R_1 + R_2) \tag{3}$$

where $B^{\Delta 2}$ and $B^{\Delta 3}$ are 2nd (15×15) and 3rd (20×20) order delta matrices defined by Castaings and Hosten [12].

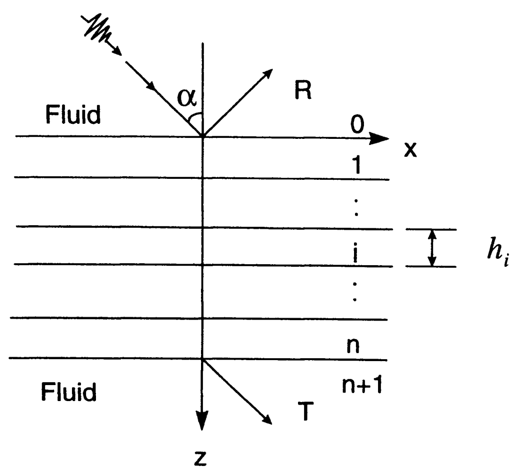


Figure 1. Geometry of fluid-loaded multilayered system.

In Eqs. (2) and (3), the coefficients a and b are given by Rohklin [5] and Nayfeh and Chimenti [4]; R and T are reflection and transmission coefficients respectively.

In order to overcome the instability, each delta element in Eqs. (2) and (3) has to be derived analytically by means of symbolic software, i.e., $6\times 6 = 36$ 2^{nd} order delta elements in Eq. (2) and $15\times 15 = 225$ 2^{nd} order delta elements and $20\times 20 = 400$ 3^{rd} order delta elements in Eq. (3). We can prove analytically that the delta matrix is inversely symmetrical and only 16 elements are independent for the 2D case. We also find that only 120 elements of the 2nd-order delta matrix and 127 elements of the 3rd-order delta matrix are independent using numerical calculations for 3D case. Because of the limited length of this paper, the 263 analytical expressions of the delta elements are not shown here.

There exists a very important multiplication rule for delta matrices: the delta matrix of a product matrix is equal to the product of the delta matrix of the individual factor matrices. Therefore the delta matrices in Eqs. (2) and (3) can be computed by multiplication of the delta matrices of each layer. This solves the loss-of-precision problem and can give high precision results for reflection and transmission coefficients.

Global Matrix Method

Knopoff [13] first developed the direct global matrix method (DGM) to avoid the large *fh* problem. The DGM method is to assemble directly a single matrix which represents the complete system. The system matrix consists of *6n* equations (Fig. 1). The equations are based on the continuous boundary conditions of displacements and stresses at each interface. The solution can be obtained from the full matrix using Gaussian elimination [14][15].

Fig. 2 compares the computation time of delta transfer and global matrix methods. It shows that the global method is preferable for small n (<64), but computation time increases rapidly with the number of layers. On the other hand, the efficiency of the delta transfer matrix method is less sensitive to the number of layers. For the problem of wave propagation in the symmetry plane of a 0°/90° lay-up composite, the delta transfer matrix method is preferable. Both methods are used to perform theoretical calculations for wave propagation in the 16-layer quasi-isotropic sample.

EXPERIMENT

Sample

The sample used in the experiment is a multi-ply laminated graphite epoxy composite. From

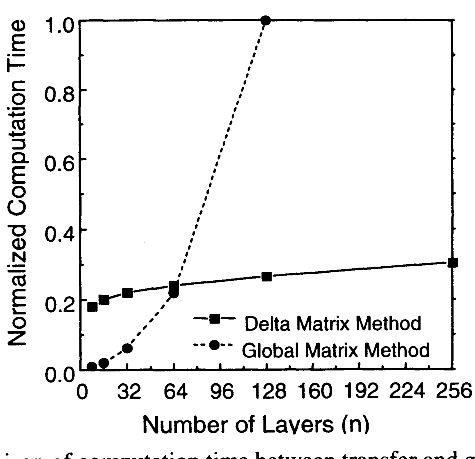


Figure 2. Comparison of computation time between transfer and global matrix methods.

Fig. 3 one can see that the composite is a symmetry structure with lay-up sequence: $[0/-45/90/45/0/-45/90/45]_s$. The laminate plate thickness is 3.1 mm within 16 plies total. The thickness of each ply is approximately 0.2 mm. It is important to notice that there is excess epoxy forming thin bonding layers between the plies which contribute to the formation of reverberation signals when the ultrasonic wave is incident in a certain frequency range (Fig. 5). Additional discussion of this phenomenon will be given in the next section.

Experiment Setup and Measurement Principles

The experiment is performed in a goniometer ultrasonic system using the double-through reflection/transmission technique [16]. Fig. 4a shows the setup of the measurement system and a schematic of the measurement technique is shown in Fig. 4b. We focus on the ultrasonic response of reflection and transmission characteristics at different incident angles α and different orientation angles θ. θ here is defined as the angle between the plane of incidence and the fiber direction of the first ply. In the goniometer system, the sample can rotate along two axes. One is for change of the incident angle α which is controlled by a CTC-283 DC Motor Controller (Micro Kinetics Co.), the other is for change of the orientation angle θ which is manually controlled. The reflected or transmitted signals are amplified, digitized, averaged by a Lecroy 9400 300MHz digital oscilloscope, and collected by the computer through IEEE-488 interface. The data can be further processed to get peak-to-peak amplitude information.

RESULTS AND DISSCUSSIONS

Normal Reflection Response

Fig. 5(a) and 5(b) give the normal reflection time domain responses from the sample composite using different broadband transducers at two center frequencies: 5MHz and 10MHz. At 5MHz, one can clearly observe the reflection echoes from the front and back surfaces. The reflection diagram is very similar to that from an isotropic plate with two parallel surfaces. The very low amplitude (close to baseline level) signals between the two echoes indicate that at 5MHz the ultrasonic signal can almost go through the plate without any influence by thin excess epoxy layers between different plies. At 10MHz, one can still clearly see the echoes reflected from the front and back surfaces; however there are reverberation signals between them caused by the signals reflected from each ply boundary. The impedance mismatch between the thin

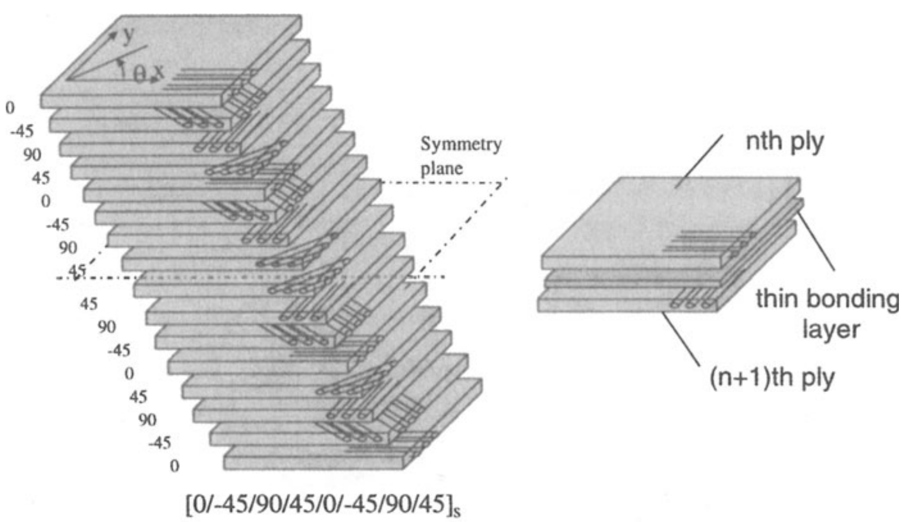
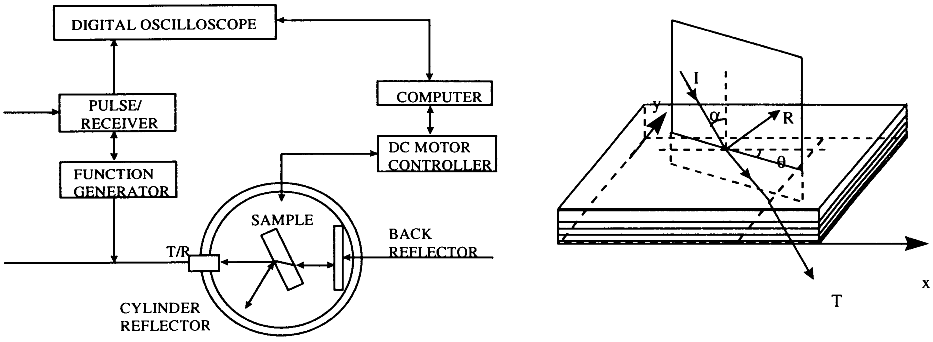


Figure 3. The lay-up of the multi-ply laminated composite sample.



(a) (b)

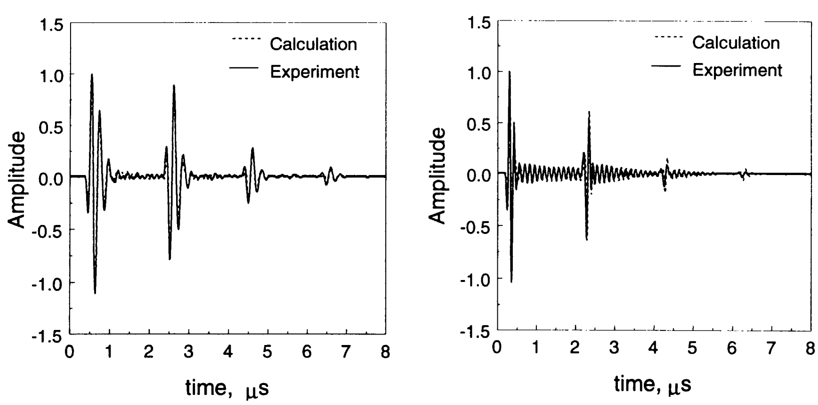
Figure 4. (a) The experimental set-up of the ultrasonic measurement system (b) Schematic of the measurement principle.

excess epoxy layer and the ply causes the reflection. In our theoretical model, we introduce a 5μm excess epoxy layer between each ply. The model predicts the reverberations and agrees very well with experiment (Fig.5b). It is obvious that one can characterize the thin layer properties such as thickness from the reverberation signals. However the reverberation signals may also mask the signals we are interested in, such as the signal from small delaminations.

<u>Double Through Transmission Amplitude</u>

One of our objectives of investigating the transmission properties of the composite is to provide information for us to evaluate joint structures made by this or similar kinds of composite plates in future. It is important to find at which incident angle, orientation angle and frequency range there is sufficient ultrasonic energy reaching the back side of the composite (reaching the adhesive layer in the composite joint case).

Fig. 6 shows experimental results for the double through transmission amplitude from 0° to 70° incident angle at four orientation angles: 0°, 25°, -25°, 90°. The incident wave is a pulse signal of center frequency 2.25MHz. From these figures one can observe that the transmission amplitude drops very fast when the incident angle changes from 0 to 10 degrees. At incident angles between 20 and 40 degrees, there is almost no transmitted energy. Then a very obvious



(a) 5 MHz (b) 10 MHz

Figure 5. Normal reflection time domain signals from the laminate (a) 5 MHz, (b)10 MHz.

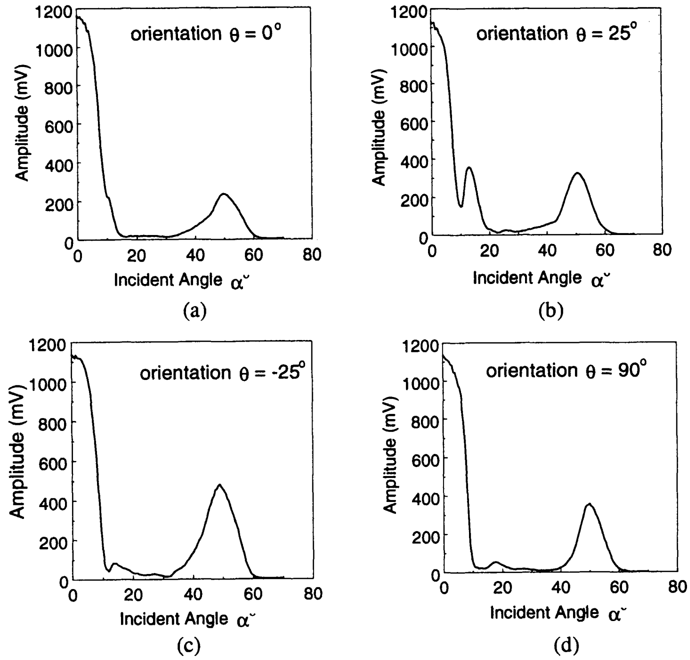


Figure 6. Measured amplitude of double transmission signal vs. incident angle α at different orientation angles θ. (a) $\theta = 0^{\circ}$, (b) $\theta = 25^{\circ}$, (c) $\theta = -25^{\circ}$, (d) $\theta = 90^{\circ}$. Frequency = 2.25 MHz.

transmission peak emerges around 50 degrees and its peak position and amplitude changes for different orientation angles. It must be noted that at certain orientation angles (such as $\theta = 25^{\circ}$ in Fig. 6(b)) there is another transmission peak around 15°. Unlike the 50° peak, which exists at orientation angles, the 15° peak only exists in a certain range of orientation angles. The time domain signals at several incident angles for plate orientation $\theta = 25^{\circ}$ are shown in Fig.7 (b). At normal incidence, the front and back surface echoes are very good and there are no reverberation signals from the excess epoxy layer between plies. At 14° incident angle, the transmitted signal reaches the first maximum and clearly shows dispersion. The amplitude drops after 14° and becomes almost the same as the base level signal at 30°. From the 30° incident angle the transmitted signal amplitude increases again and reaches a second maximum at 50°. Spectrum analysis shows the transmitted signal has a center frequency of about 2MHz at 50° incident angle.

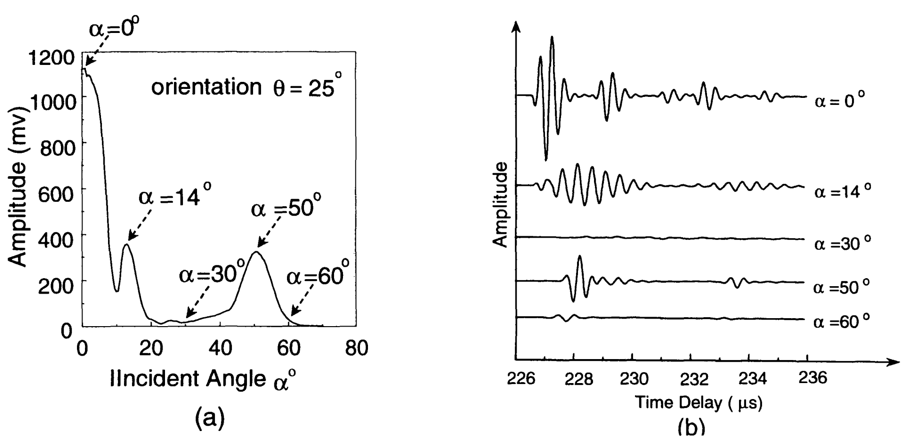


Figure 7. Measured double through transmission characteristics at orientation angle $\theta = 25^{\circ}$. (a) Amplitude curve at different incident angles. (b) Waveforms at corresponding incident angles in (a). Incident wave: 2.25MHz pulse.

To further investigate the transmission properties of the composite, double through transmission measurements were carried out at orientation angles from 0° to 180° with steps of 2°. The transmission amplitude is represented in the images of Fig. 8. In these images, the radial direction represents the incident angle α and the circumferential direction represents the orientation angle θ. The gray level represents the amplitude; the darker the gray level, the higher the amplitude level. By comparing both the calculation and experimental results, one can see the following: (1) The double through transmission amplitude has 180° rotation symmetry; (2) It has no reflection symmetry (θ and $-\theta$); (3) It definitely shows no isotropic characteristics; (4) It is very interesting that both experiment and theoretical calculation show and agree very well that there is a transmission peak when $10° < \alpha < 20°$ and $10° < \theta < 75°$. The transmitted signals at this peak are clearly dispersion signals; (5) There is always a transmission peak around $\alpha = 50°$ for all the orientation angles. However the peak position, width and amplitude are slightly different at different orientation angles θ.

For the pulse signal with 2.25MHz center frequency, it is clearly shown from Fig. 8 that there is an incident angle range around 50° allowing the energy to be transmitted. But it is also very important to know whether this transmission peak exists when the frequency increases. Fig. 9 compares the double transmission amplitude for both 2.25MHz pulse and 5MHz tone burst signal cases at orientation angle 45°. At 5MHz, very little energy is transmitted through the plate around incident angle α=50°. Theoretical calculation also shows similar results. This puts a limit on using higher frequency signals to investigate the adhesive joints made from this composite plate.

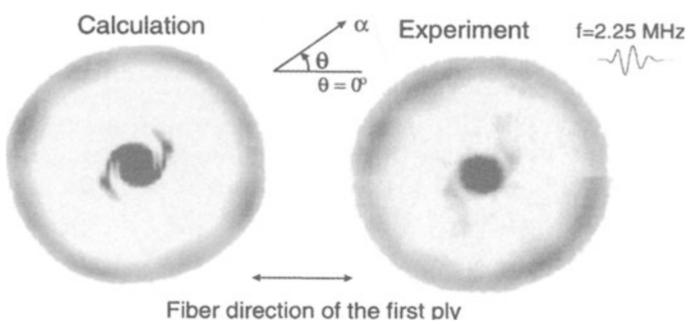


Figure 8. Amplitude of double through transmission signals at different incident and orientation angles (experiment and calculation).

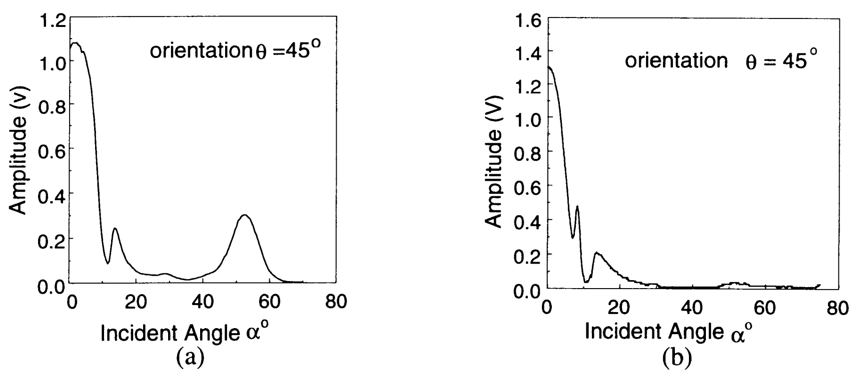


Figure 9. Measured amplitude of double transmission signal vs. incident angle α at orientation angle $\theta = 45°$. The incident signals are (a) 2.25 MHz pulse, (b) 5MHz tone burst.

CONCLUSIONS

In this paper propagation of ultrasonic waves in arbitrary directions of multilayered quasi-isotropic composites is investigated theoretically and experimentally. Both δ transfer and global matrix methods are used for calculation. It was found that for an arbitrary lamina orientation the global method is more efficient for number of layers below 64. The transfer matrix method is preferable for any number of layers in the plane of symmetry for a $0^{\circ}/90^{\circ}$ composite lay-up. Experiments were performed for a 16-layer quasi-isotropic graphite epoxy composite using both transmission and reflection measurements. Good agreement is observed between theoretical and experiment results. While for static mechanical properties the material is transverse isotropic with isotropy axis perpendicular to the composite surface, the ultrasonic response exhibits monoclinic symmetry at frequency about 2 MHz. Ultrasonic wave transmission decays very fast with increasing deviation of the incident angle from the normal direction. A transmission window is found at angle about 50° at central frequency 2.25MHz. This makes it possible to use obliquely incident waves for composite evaluation. However the ultrasonic behavior is highly frequency dependent and scattering is significant for wave propagation at higher frequencies.

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